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THESIS

A PROBABLE BREAKDOWN MECHANISM IN THE
ELECTRON BEAM SUSTAINED CO₂ LASER.

by

Rodney Deayne/Timm

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Thesis Advisor:

F. Schwirzke

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A Probable Breakdown Mechanism in the
Electron Beam Sustained CO₂ Laser

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

A stable high-pressure electric discharge is produced using an electron-beam to ionize the gas in the CO_2 - N_2 - He laser. The important electron loss process in this type of discharge are recombination and attachment. The prominent instability in the non-self-sustaining discharge is the streamer which leads to arcing and complete breakdown of the gas. A qualitative analysis of streamer formation based on the ionization and resultant electron production of secondary electrons to setup an avalanche starting the chain which produces a highly conductive channel and results in the complete breakdown of the gas is presented. The onset of streamer formation at the anode is aided by local release and ionization of neutral atoms. The resulting increase of the plasma pressure leads to an increase of the potential and the onset of unipolar arcing.

TABLE OF CONTENTS

I.	INTRODUCTION -----	6
II.	QUALITATIVE ANALYSIS -----	9
III.	EXPERIMENTAL APPARATUS -----	25
IV.	CONCLUSIONS -----	27
	LIST OF REFERENCES -----	29
	BIBLIOGRAPHY -----	30
	INITIAL DISTRIBUTION LIST -----	32

I. INTRODUCTION

Stable high density plasma discharges have many applications in plasma physics. A significant example is the use of these discharges in high-power gas lasers. This paper will attempt to describe an instability in the externally ionized, electron-beam sustained, carbon dioxide laser--that being the formation of a streamer leading to a glow-to-arc transition.

Classically, stable plasma discharges are produced by working in the region where diffusion of the charged species to the walls stabilizes the discharge. The electron temperature in the discharge is raised until the ionization rate due to these electrons equals the rate at which electron-ion pairs recombine at the walls. In this case the electron temperature is controlled by varying the electric field. At higher pressures, the diffusion time is not a factor because it generally becomes longer than the time characteristics for the onset of instabilities in the plasma and the formation of discharge spokes or arcs. Many of the instabilities in the plasma are associated with the ionization process and and its coupling with the electron temperature.

One can achieve separation of plasma ionization from the electron temperature by utilizing a beam of high-energy electrons to create a uniform ionization throughout the

volume of the plasma or the working medium. Using the high energy electrons to provide the ionization, the electron temperature is varied independently by adjusting the sustainer electric field. If the electron temperature is maintained low enough so that the ionization due to the discharge electrons is small compared to the ionizations due to the high-energy electrons, the discharge should remain uniform over a wide range of pressures up to and above atmospheric pressure. As the electric field is raised, the ionization by the discharge electrons becomes substantial and the discharge becomes nonuniform and will eventually arc. A stable discharge should be obtained when the volumetric secondary electron loss rates due to electron-ion recombination and electron-neutral attachment equal the volumetric secondary electron production rate by the electron beam. The recombination and attachment coefficients are an important parameter in determining the level of ionization obtainable with a given electron beam.

Discharges using the electron beam to ionize the plasma are used in order to maximize laser outputs from high pressure gases. The process is used in the $10.6\mu\text{-CO}_2$ laser discharge and the principle is also being used for CO and HF lasers. In papers written concerning the electron beam, sustained discharges it appears that the most prominent instability is that of the streamer formation leading to

arching and complete breakdown in the discharge. Onset of streamer formation occurs preferentially on the surface of the anode.

II. QUALITATIVE ANALYSIS

A breakdown mechanism in the electron-beam sustained CO₂ laser will be discussed. One of the basic difficulties of an ordinary discharge laser stems from the dual role expected of the free electrons in the working medium. They must move through the discharge under the influence of the applied electric field, producing new electron-ion pairs by collision to offset the losses by dissociative attachment, dissociative recombination and ambipolar diffusion to the walls. Simultaneously these same electrons must excite gase molecules by collision to populate the upper laser state and bring about the inversion required for lasing conditions. One problem is that the optimum in the electron temperatures required for these two jobs in general are not the same. The laser works best at one value of electron temperature and the discharge may be stable only at a different higher value. With the advent of the electron beam, this dual role for the electrons to ionize and excite the lasing medium has been separated. The electron beam produces the high-energy electrons ≈ 200 keV, $n_e \approx 10^6$ cm⁻³ which are fired into the laser medium to maintain the discharge by the production of relatively low-energy secondary electrons of density $n_e \approx 10^{11} - 10^{13}$ cm⁻³ that carry the current ($\approx 3 \times 10^{-3}$ A/cm²)

across the discharge field ($\approx 10\text{kV/cm}$) and current density of $\approx 2\text{A/cm}^2$ excite the laser levels. Figure 1 is a schematic representation of an electron-beam sustained laser.

Attachment instabilities [Reference 1] occur when the differential gas conductivity becomes negative (i.e., a local increase in the electric field results in dissociation of CO_2 into O^- and thus in the lowering of the electron density due to attachment causing a lowering of the conductivity) due to enhanced electron attachment by neutral molecules at high electric fields. The attachment instability being significant at high electric fields and low pressures for many gases. Thermal and acoustic instabilities [Reference 2] provide limits on the total energy that can be introduced into the discharge. As pointed out by Nighan and Weigand [Reference 3] vibrational instabilities exist when significant energy is stored in molecular vibrational modes; increases in gas temperature accelerate the collisional transformation of this energy to translational, resulting in run-away heating of the discharge medium.

Both attachment and thermal-acoustic instabilities are large-scale column instabilities, only the initial phase of their growth can be described by linear analysis. The secondary phase of these instabilities is the formation of discharge streamers. Non-self-sustaining discharges (i.e., the electron-beam sustained discharge) must be distinguished

from the electron-avalanche type of streamer appearing in spark breakdown. Streamers of this type have been found to occur quite commonly in such discharges and are responsible for arcing in many high power gas discharge lasers.

Statistically, one can describe a streamer as a cylinder of hot and consequently conductive gas (because of its lower density and increased ionization at the higher streamer electron temperature). This conducting cylinder protrudes into the discharge creating a stronger field in comparison to a homogeneous discharge and higher current density at the tip, acting as what would occur near the tip of a wire protruding from either the cathode or anode. Both the field and current density act to raise the conductivity of the gas around the tip, the field by increased ionization and the current density by increased heating. The streamer grows across the discharge at a velocity determined by the time required to heat the gas up to a high enough temperature, assuming density is inversely proportional to temperature. This will increase the electron mobility μ and hence its conductivity:

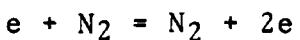
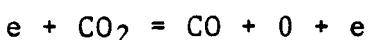
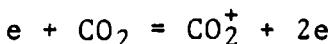
$$\sigma = \frac{n_e \mu_e}{N} \quad (1)$$

where n_e is electron density, e is electron charge and N is gas density. When the streamer reaches the appropriate electrode (cathode or anode), or joins with a streamer

propagating from the opposite electrode, then a low impedance circuit is formed and most of the discharge current flows through this low impedance channel interrupting the main discharge.

In regards to the importance of charge particle production and loss processes in the gas discharge the chemistry of the CO₂-N₂-He discharge follows. Electron impact dissociation of CO₂ and N₂ leads to the formation of CO, O and to a lesser extent N, with the result that a significant number of minority molecular species composed of carbon, oxygen and nitrogen are produced. The dominant particle reactions occurring in the CO₂ laser medium for lasing condition are [Reference 4]:

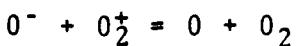
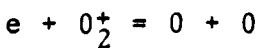
1. Direct electron impact ionization and dissociation of the principal molecular constituents, CO₂ and N₂



2. O⁻ formation resulting from dissociative attachment to CO₂



3. Dissociative recombination of the principal positive ions



4. Associative detachment of electrons from negative ions



The concentration of the principal molecular constituents remain essentially unchanged, which permits the continued use of the set of ionization, attachment and dissociation rates. The principal dissociation products of CO, O and N, which result from direct electron impact on CO₂ and N₂ accumulate rapidly and reach concentrations on the order of one percent of the initial species in approximately 10⁻² seconds where typical gas residence times in laser discharges are 10⁻³ to 10⁻² seconds [Reference 4]. One percent of CO₂ at atmospheric pressure would lead to an O⁻ concentration of 5 x 10¹⁶ cm⁻³, since n_e ≈ 10¹² cm⁻³ attachment will be severe.

In electron beam controlled gas discharges, the high vacuum electron gun is separated from the working gas cavity by means of a thin foil (typically 1-mil aluminum or titanium). The high energy electrons from the gun undergo collisions in passing through this foil which decreases their energy. In the cavity an applied electric field adds energy to the electrons in an amount nearly equal to the energy loss through the foil and losses in traveling through the working medium [Reference 5]. Upon traversing the foil and the distance between anode and cathode some scattering takes place. The volume ionization may be larger than desired outside the working volume thus producing a plasma which is to some degree non-uniform. The electron beam is utilized to ionize the gas

and thus transform the gas into a conducting plasma independent of the applied sustainer potential. By this means it is possible to close a value of the electric field which is most efficient to pump the CO₂ lasing levels. The electron-beam controls and maintains a rather uniform plasma density and thus a uniform electric field within the working medium of the laser. Any transition to another non-uniform mode of discharge can lead to the occurrence of breakdown.

Nasser [Reference 6] in his text, "Fundamentals of Gaseous Ionization and Plasma Electronics" develops the condition for which glow to arc transitions occur in both a uniform and non-uniform electric field. In relation to the electron-beam sustained discharge which produces a rather uniform plasma in the working medium a qualitative explanation will be given to a probable cause of breakdown. As the electrons produced from the electron gun pass through the inhomogenous stronger field near the cathode rods of the sustainer field they can produce ionizations and excitation of the gases. Looking at an electron that starts at the cathode, it builds up an avalanche of electrons through these ionizations occurring within the laser medium. Within the avalanche, excited states of the medium have short lifetimes, so long before the primary avalanche has reached the anode, photons are emitted from these excited states, (Figure 2a). These photons head in all directions and may be absorbed at a certain distance from their origin, producing photo-electrons.

These new photo-electrons are created in the gas and some become available to the primary avalanche that is still advancing towards the anode (Figure 2b). As this avalanche advances toward the anode and reaches a critical size, a space charge field will be created of the same order of magnitude as the original field. Such field enhancement can effectively increase the ionization yields of the secondary avalanches, (Figure 2c), started by the photo-electrons. These secondary or auxiliary avalanches will also emit photons as they are being formed. The resulting space charge field will distort the original field lines. This process may be the cause of irregular branching in the streamer. Positive ions created by the primary avalanches will proceed towards the cathode gradually including the charges of auxiliary avalanches (Figure 2d and 2e). This constitutes the growth of an ionized channel from the anode to the cathode. The electrons in the tips of the auxiliary avalanches are absorbed by the positive space charge and the streamer has formed two branches that are growing as a result of the on-coming avalanches (Figure 2f). The electron movement in the channel toward the anode is by virtue of the potential gradient within the channel. Ionization by electron collision is a varying quantity that is dependent on the electron energy and hence on the field. If the E-field is high for example near the cathode and anode rods, the probability that an electron will form an avalanche is also high. This

probability being high will insure that an adequate number of avalanches feed the streamer tip and keep it advancing towards the cathode.

The criterion for complete breakdown to occur is based on the assumption that one avalanche has reached a critical size that triggers the growth of a streamer. The avalanche should produce a space charge field of the same order of magnitude as the applied sustainer field.

As described earlier, at the anode where a space charge is created it is possible that an anode spot may be formed which would aid in the development of the glow to arc transition. The model proposed is that of the unipolar arc model. In the cavity, assuming plane electrodes, a linear field is in existence that would appear as in Figure 3. Although this potential appears linear, there is a region of higher field strength near the cathode and anode known as the cathode fall and anode fall. At the anode this region appears as in Figure 4. The anode zone distance is on the order of the Debye length λ_D :

$$\lambda_D = \left(\frac{k T_e}{4\pi n_e e^2} \right)^{1/2} \quad (2)$$

If in fact near a spot on the anode, n_0 (the neutral gas concentration) increases by desorption of gas from the anode surface and metal evaporation. A fraction of the neutrals will be ionized and a plasma pressure gradient is set up near the anode such that:

$$\Delta p = -e n_e E \quad \text{or} \quad E = -\frac{k T_e}{e} \frac{1}{n_e} \nabla n_e \quad (3)$$

if $k T_e$ is constant. The current density across the medium is constant and given by:

$$j = \sigma E \quad (4)$$

where j is the current density, σ is the conductivity and E is the field. The conductivity (σ) is given by:

$$\sigma = \frac{n_e}{n_0} \frac{e^2}{m} \frac{1}{v_{TH} \sigma_{coll}} \quad (5)$$

where n_e is the electron density, n_0 is the neutral gas density, m is the electron mass, v_{TH} is the electron thermal velocity and σ_{coll} , the collision cross section. In a gas, heating leads to a decrease in n_0 . Near a surface, heating can lead to an increase in metal influx, $\frac{dn_e}{dt} > 0$. Therefore near a surface (in this case the anode) if n_0 increases this implies that σ decreases and E must increase to maintain the current density (j) constant. Heating of the gas follows the formula:

$$\dot{Q} = \sigma E^2 \quad (6)$$

Since E has increased this implies that the heating of the gas near the surface at the anode increases further. An increase of the neutral density in the anode region results in a local increase of ionization at the anode by the electron beam. This increase of ionization leads to an increase in the electron density at the anode. Equation 4 implies that

the conductivity is proportional to $\frac{n_e}{n_0}$ which may lead to an increase in the conductivity. The ionization energy for metals is less than that for gases therefore it is felt that the plasma density will further increase. The locally higher plasma density causes the plasma potential to increase. The locally higher pressure region near the anode, the modified potential and reduced Debye length may appear as in Figure 5. This implies that the field can become non-uniform near the anode due to the space charge build up such that the plasma becomes even more positive than the anode. Therefore a unipolar arc could be the initial phase of streamer formation at the anode.

Within the anode region a spot can be formed acting now like the cathode spot in the unipolar arc model, where the temperature of the spot is increased so as to have a strong local emission of electrons and metal vapor into the plasma at a higher positive potential in front of the anode. Once this condition is met, a circulation current is formed such that the current flowing from the regions of negative potential return to the anode, Figure 6. This discharge where the metal surface acts as both cathode and anode is known as the unipolar arc [Reference 7]. The locally increased positive potential of the higher plasma pressure region will further enhance the number of avalanches feeding the space potential allowing the streamer to grow toward the cathode

and complete the glow to arc transition. It appears that this action can enhance the growth rate of the streamer channel. To verify this analysis, the anode of an electron-beam sustained laser and/or an anode plate that has been exposed to an electron beam should be investigated to see if arc tracks are present.

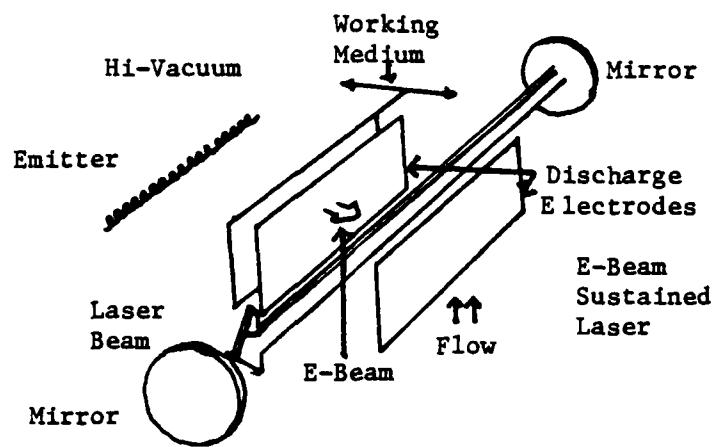


Fig. 1 A schematic representation of an E-beam sustained laser

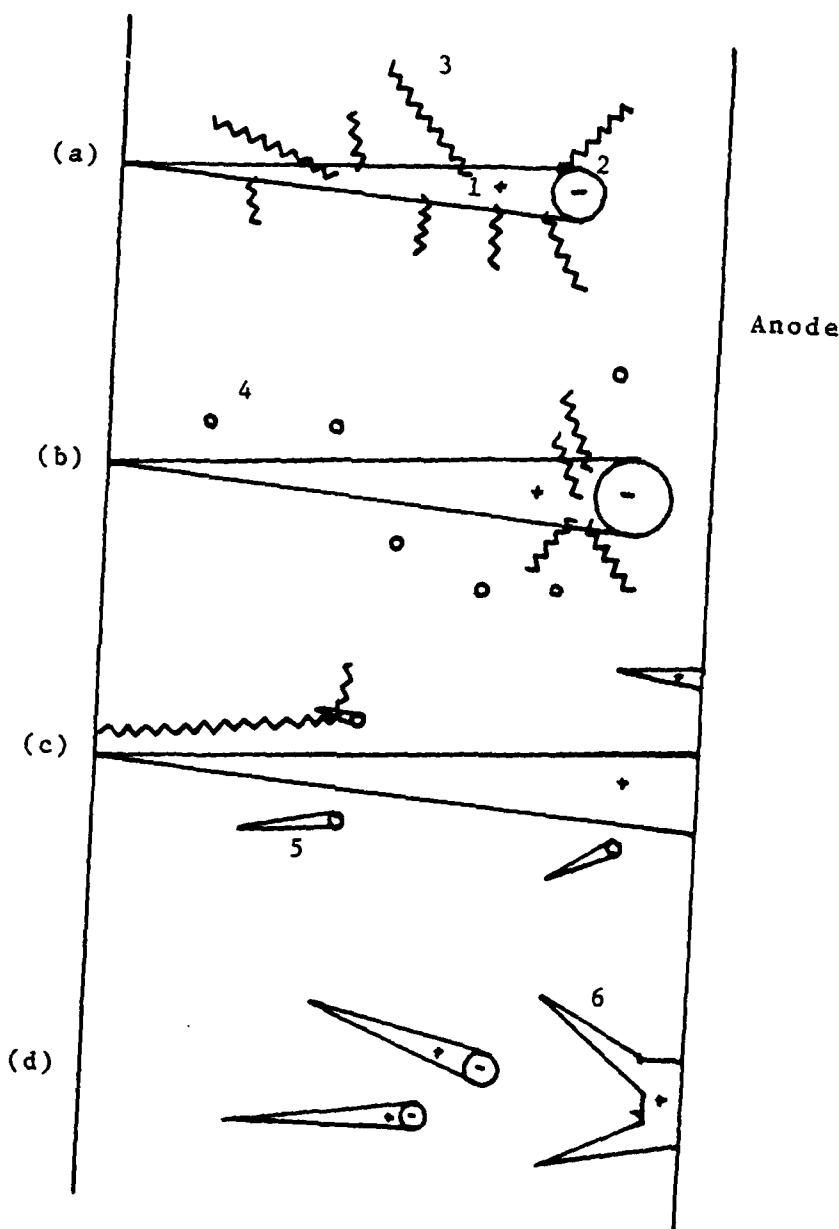


Fig. 2

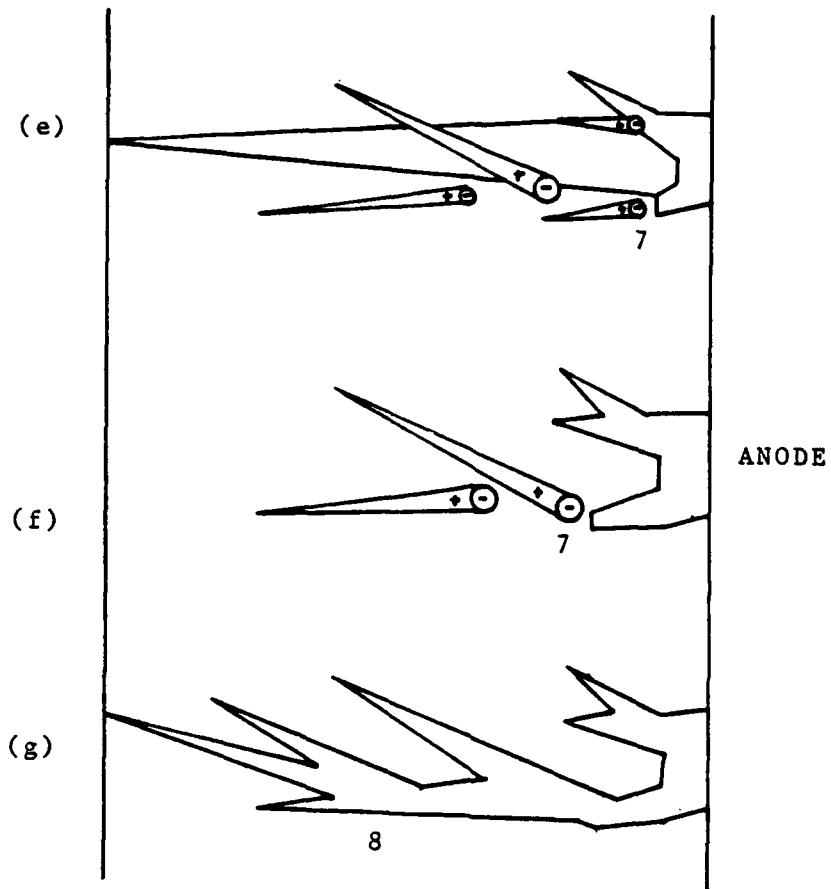


Fig. 2 A schematic diagram depicting the development of
(contd.) an avalanche to a streamer in a uniform field:

1. Positive space charge of an avalanche.
2. Negative space charge of an avalanche.
3. Photons emitted from the avalanche.
4. Photo-electrons.
5. Auxiliary avalanches produced by photo electrons.
6. Streamer tip.
7. Propagating streamer tip by the feeding avalanches.
8. The completed streamer with branches.

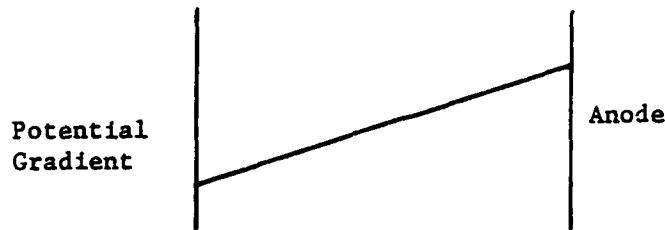


Fig. 3 Linear potential gradient across the working medium of a CO_2 laser.

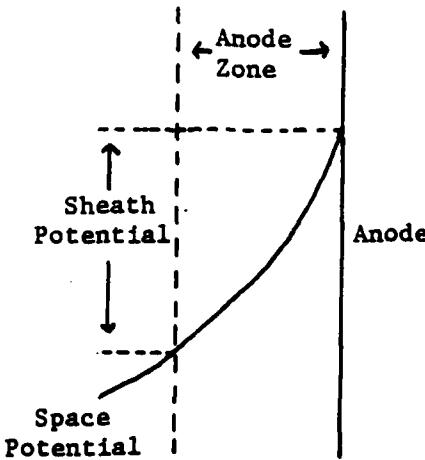


Fig. 4 Potential distribution of the anode region.

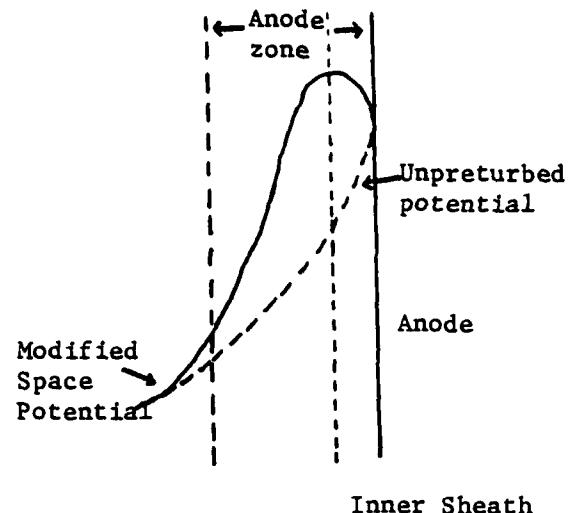


Fig. 5 Potential distribution due to positive space charge build up caused by a local plasma pressure increase.

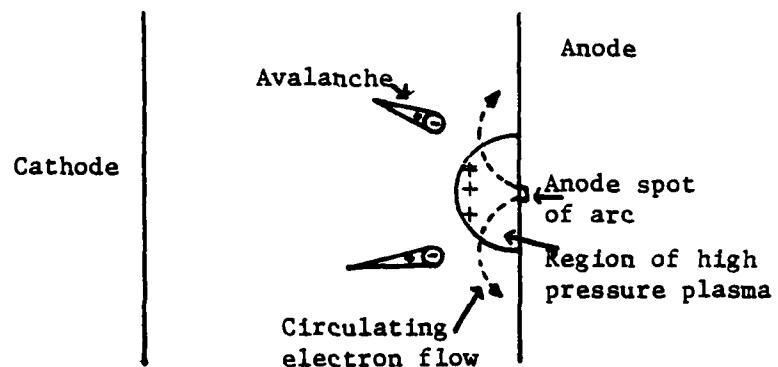


Fig. 6 Circulating electron flow in region of high pressure plasma at the anode.

III. EXPERIMENTAL APPARATUS

The basic equipment for experimental usage of an electron-beam discharge is on board the Naval Postgraduate School. A schematic diagram of the equipment is shown in Figure 7. This equipment has been obtained to carry out experiments involving the electron-beam sustained laser to investigate the causes of arcing in the lasing medium.

At this time, no actual experiments have been performed due to the time constraints in obtaining the equipment and subsequent lack of funding for this project. Major equipment missing is the sustainer power supply. The vacuum pump has been serviced to make it operational. Other items need some attention before the system will be ready.

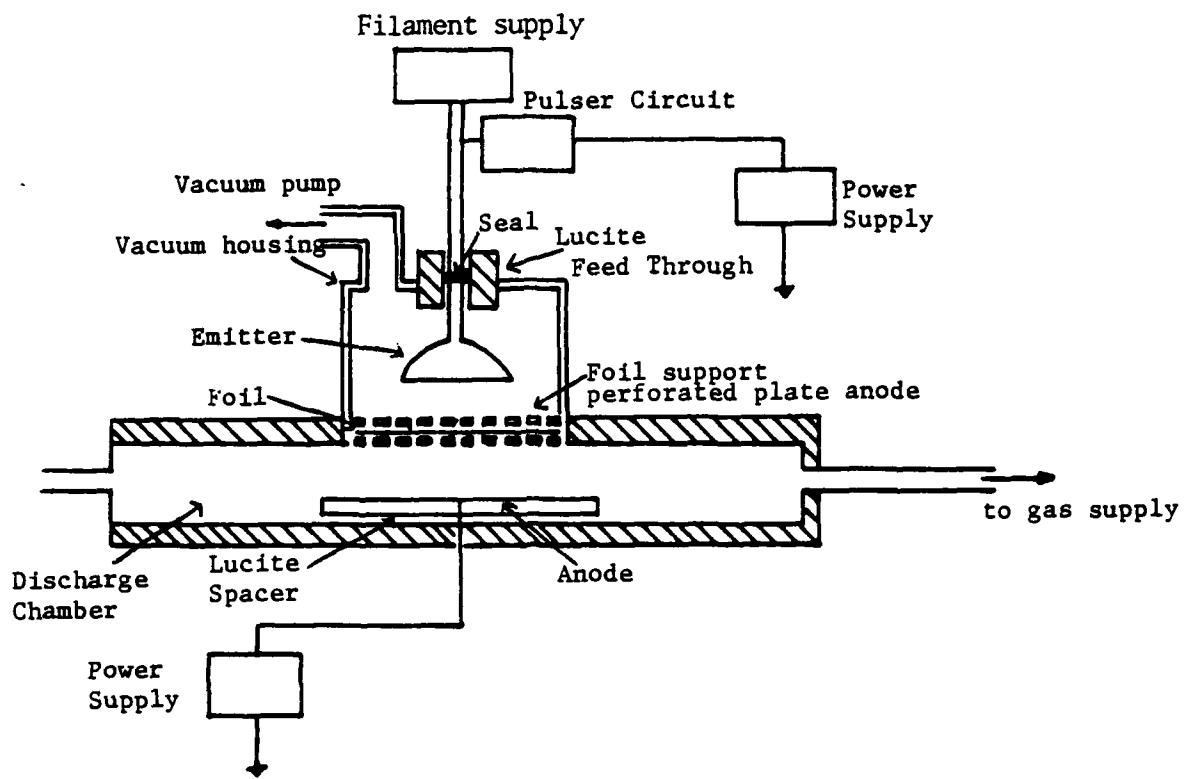


Fig. 7 Schematic drawing of electron beam sustained discharge.

IV. CONCLUSIONS

Breakdown occurs by streamer formation on the anode and cathode. Local surface heating leads to influx of neutrals and increased plasma pressure due to ionization by the e-beam. The modified plasma potential allows the onset of unipolar arcing on the electrodes. Streamer propagation through the discharge is aided by avalanches.

On its way to the anode, the avalanche reaches a critical size (determined by the space charge produced by the avalanche) such that secondary electrons begin to be generated just ahead of the avalanche by photoionization of the gas caused by the ionizing radiation generated in the avalanche. Of these electrons there is a group located just ahead of the avalanche that is in a region of high field due to the enhancement caused by the avalanche space charge. In this region the electrons can further multiply generating a space charge cloud which grows at a position closer to the anode. Since the photons generating secondary electrons propagate at the speed of light, and since the subsequent growth of the space charge is fast (due to the enhanced field), the propagation time is very small.

This presentation is only qualitative in nature and the question that must be answered experimentally is to measure

the spectrum of radiation generated in the lasing medium to determine and explain the proposed nature of the process of photoionization ahead of the avalanche. It is proposed that ionization of atoms excited by photons are responsible for the formation and propagation of the streamer.

The unipolar arc model must also be investigated in the region of the anode to verify if this arc can enhance streamer formation and growth.

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